PATTERN FORMING METHOD AND

APPARATUS FOR FABRICATING SEMICONDUCTOR DEVICE

BACKGROUND OF THE INVENTION

5   The present invention relates to a method for forming a
fine-line resist pattern by exposing a resist film to extreme
ultraviolet (EUV) radiation through a photomask and also re-
lates to an apparatus for fabricating a semiconductor device
by utilizing the pattern forming method.

10   As semiconductor devices for a semiconductor integrated
circuit have been downsized, it has become increasingly ne-
cessary to further reduce the feature size of a line-and-space
pattern.   And to define a fine-line pattern, a lithography
technique is indispensable. Particularly when a pattern with

15   a line width of $0.07\,\mu$m or less should be defined, a lithogra-
phy technique using EUV radiation with a wavelength of around
13 nm as an exposing radiation is expected to be very effec-
tive.

      In a known lithographic process using krypton fluoride

20   (KrF) excimer laser radiation (with a wavelength of around
248 nm) or argon fluoride (ArF) excimer laser radiation (with
a wavelength of around 193 nm), an exposure process is car-
ried out in the air or nitrogen ambient.   However, if the
same exposure process is performed in such an ambient using

25   EUV radiation, then the radiation is absorbed into oxygen or

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nitrogen molecules contained in the ambient, because the EUV radiation has a much shorter wavelength. This is why the EUV exposure process should be carried out in a vacuum.

For that reason, a known process of forming a resist pattern out of a chemically amplified resist material, for example, using the EUV radiation is carried out in the following manner.

First, a chemically amplified resist material is applied onto a substrate in the air to deposit a resist film thereon. Next, the resist film is pre-baked to vaporize a solvent contained in the resist film.

Then, the resist film is exposed through a photomask to EUV radiation in a vacuum, thereby transferring the pattern of the photomask onto the resist film.

Subsequently, the resist film is subjected to a post-exposure baking process in the air so that the acid diffuses in the exposed or non-exposed parts of the resist film. Finally, the resist film is developed using a developer, thereby defining a resist pattern.

Where a resist pattern should be formed out of a non-chemically-amplified resist material, the resist film is exposed through a photomask to EUV radiation in a vacuum and then developed immediately in the air without being subjected to the post-exposure baking process.

The present inventor tentatively defined a resist pat-

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tern by exposing a resist film to EUV radiation and then pat-
terned a film on a substrate by dry-etching it using the re-
sist pattern obtained. As a result, I found that the walls of
the patterned film showed a non-negligibly high degree of
5 roughness.

SUMMARY OF THE INVENTION

An object of this invention is reducing the roughness at
the walls of a patterned film to a negligible degree where
10 the patterned film is obtained by dry-etching an original
film using, as a mask, a resist pattern defined through expo-
sure of a resist film to EUV radiation.

I carried out intensive research to understand why the
walls of a patterned film showed an increased degree of
15 roughness where the patterned film had been formed by dry-
etching an original film using, as a mask, a resist pattern
defined through exposure of a resist film to EUV radiation.
As a result, I found the following.

Firstly, in an EUV exposure process, a resist film is
20 exposed to EUV radiation with as high an energy as about 100
eV in a vacuum, thus degassing the resist film. A gas (e.g.,
CO_2 gas), given off from the resist film, produces some reac-
tants (e.g., CO_x (where $x < 2$)), which soon deposit themselves
on the walls of a resultant resist pattern to increase the
25 roughness at the walls of the resist pattern. For that rea-

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son, the walls of the film patterned would also increase their roughness because the roughened pattern is transferred as it is onto the film.

Also, where a patterned film is formed by plasma-etching
5   an original film using the resist pattern, a gas (e.g., CO_2 gas) emanated from the resist film mixes with the plasma generated in a chamber. Accordingly, the chemical composition of the plasma is subject to change during the plasma etching process, thus eventually increasing the roughness at the
10   walls of the patterned film.

Furthermore, where a resist film is formed out of a chemically amplified resist material, the resist film is pre-baked in the air and then transported to the vacuum chamber of an exposure apparatus as described above. However, during
15   this transportation, the surface of the resist film might be affected by an alkaline substance such as ammonia to possibly form an insoluble layer, which is hard to dissolve in an al-kaline developer, on the surface. In that case, it is very difficult to form a fine-line resist pattern as intended.

20   I acquired the basic idea of this invention from these findings.

Specifically, a first inventive pattern forming method includes the steps of: a) forming a resist film out of a re-sist material on a substrate; b) pre-baking the resist film;
25   c) exposing the pre-baked resist film to extreme ultraviolet

radiation through a photomask; and d) developing the exposed resist film, thereby defining a resist pattern on the substrate. In this method, the steps b) and c) are carried out in a vacuum without subjecting the resist film to the air.

5   A second inventive pattern forming method includes the steps of: a) forming a resist film out of a resist material on a substrate in a first processing chamber filled with the air or an inert gas; b) pre-baking the resist film in a second processing chamber filled with a vacuum; c) transporting

10   the pre-baked resist film in line to a third processing chamber filled with a vacuum and then exposing the pre-baked resist film to extreme ultraviolet radiation through a photomask in the third processing chamber; and d) transporting the exposed resist film in line to the first processing

15   chamber and then developing the exposed resist film in the first processing chamber, thereby defining a resist pattern on the substrate.

In the first and second pattern forming methods, the pre-baking step b) is carried out in a vacuum, not in the air

20   unlike the known process, so a gas like CO_2 gas is given off from the resist film in this pre-baking step b). Accordingly, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step c). That is to say, in

25   this exposing step c), the reactants, usually produced by the

CO_2 gas, etc., emanated from the resist film during the exposure, will not deposit themselves on the walls of the resultant resist pattern. This is because the gas has already been released in the previous step b). Thus, those walls of

5 the resist pattern much less likely increase their roughness. As a result, the walls of the patterned film will not increase their roughness, either.

Particularly, according to the second method, the prebaking and exposing steps b) and c) are performed in mutually

10 different processing chambers. In addition, a much smaller quantity of gas is released in the exposing step c). Accordingly, almost no reactants will deposit themselves on the surface of the resist film, photomask or optical system including mirrors. Consequently, the resist pattern will not

15 be deformed or the EUV radiation exposure dose will not decrease.

A third inventive pattern forming method includes the steps of: a) forming a resist film out of a chemically amplified resist material on a substrate; b) pre-baking the resist

20 film; c) exposing the pre-baked resist film to extreme ultraviolet radiation through a photomask; d) post-baking the exposed resist film; and e) developing the post-baked resist film, thereby defining a resist pattern on the substrate. In this method, the steps b), c) and d) are carried out in a

25 vacuum without subjecting the resist film to the air.

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A fourth inventive pattern forming method includes the steps of: a) forming a resist film out of a chemically amplified resist material on a substrate in a first processing chamber filled with the air or an inert gas; b) pre-baking the resist film in a second processing chamber filled with a vacuum; c) transporting the pre-baked resist film in line to a third processing chamber filled with a vacuum and then exposing the pre-baked resist film to extreme ultraviolet radiation through a photomask in the third processing chamber; d) transporting the exposed resist film in line to the second processing chamber and then post-baking the exposed resist film in the second processing chamber; and e) transporting the post-baked resist film in line to the first processing chamber and then developing the post-baked resist film in the first processing chamber, thereby defining a resist pattern on the substrate.

In the third and fourth pattern forming methods, the pre-baking step b) is carried out in a vacuum, not in the air unlike the known process, so a gas like CO_2 gas is given off from the resist film in this pre-baking step b). Accordingly, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step c). That is to say, in this exposing step c), the reactants, usually produced by the CO_2 gas, etc., emanated from the resist film during the expo-

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sure, will not deposit themselves on the walls of the resul-
tant resist pattern. This is because the gas has already
been released in the previous step b). Thus, those walls of
the resist pattern much less likely increase their roughness.
5 As a result, the walls of the patterned film will not in-
crease their roughness, either.

In addition, the post-baking step d) is also performed
in a vacuum, so the gas like CO_2 gas emanates again from the
resist film at this post-baking step d). Accordingly, where
10 a patterned film is formed by etching an original film with a
plasma, the gas released from the resist film will not mix
with the plasma generated in a chamber. This is because the
post-baking and plasma etching process steps are carried out
in mutually different (i.e., the second and first) chambers.
15 For that reason, the chemical composition of the plasma will
not change during the plasma etching process, so the walls of
the patterned film will not increase their roughness.

Furthermore, the pre-baking, exposing and post-baking
steps b), c) and d) are performed in a vacuum without sub-
20 jecting the resist film to the air. Thus, the resist film,
made of a chemically amplified resist material, is not af-
fected by an alkaline substance like ammonia contained in the
air, and no insoluble layer, difficult to dissolve in an alka-
line developer, is formed on the surface of the resist film.
25 Consequently, a fine-line resist pattern can be formed just as

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intended.

Particularly, according to the fourth method, the pre- and post-baking steps b) and d) are performed in a chamber different from the chamber in which the exposing step c) is

5   performed.   In addition, a much smaller quantity of gas is released in the exposing step c).   Accordingly, almost no re- actants will deposit themselves on the surface of the resist film, photomask or optical system including mirrors.   Conse- quently, the resist pattern will not be deformed or the EUV

10 radiation exposure dose will not decrease.

A fifth inventive pattern forming method includes the steps of: a) forming a resist film out of a chemically ampli- fied resist material on a substrate; b) pre-baking the resist film; c) exposing the pre-baked resist film to extreme ul-

15 traviolet radiation through a photomask; d) post-baking the exposed resist film; e) forming a silylated layer selectively on the surface of the post-baked resist film; and f) dry- developing the resist film, on which the silylated layer has been formed, using the silylated layer as a hard mask, thereby

20 defining a resist pattern on the substrate.   In this method, the steps b), c), d), e) and f) are carried out in a vacuum without subjecting the resist film to the air.

A sixth inventive pattern forming method includes the steps of: a) forming a resist film out of a photoresist mate-

25 rial on a substrate in a first processing chamber filled with

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the air or an inert gas; b) pre-baking the resist film in a second processing chamber filled with a vacuum; c) transporting the pre-baked resist film in line to a third processing chamber filled with a vacuum and then exposing the pre-baked

5 resist film to extreme ultraviolet radiation through a photo-mask in the third processing chamber; d) transporting the exposed resist film in line to the second processing chamber and then post-baking the exposed resist film in the second processing chamber; e) transporting the post-baked resist

10 film in line to a fourth processing chamber filled with a vacuum and then forming a silylated layer selectively on the surface of the post-baked resist film in the fourth processing chamber; and f) transporting the resist film, on which the silylated layer has been formed, in line to a fifth proc-

15 essing chamber filled with a vacuum and then dry-developing the resist film, having the silylated layer thereon, using the silylated layer as a hard mask in the fifth processing chamber, thereby defining a resist pattern on the substrate.

In the fifth and sixth pattern forming methods, the pre-

20 baking step b) is carried out in a vacuum, not in the air un-like the known process, so a gas like CO_2 gas is given off from the resist film in this pre-baking step b). Accordingly, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon

25 rarely occurs in that exposing step c). That is to say, in

this exposing step c), the reactants, usually produced by the CO_2 gas, etc., emanated from the resist film during the exposure, will not deposit themselves on the walls of the resultant resist pattern, because the gas has already been

5 released in the previous step b). Thus, those walls of the resist pattern much less likely increase their roughness. As a result, the walls of the patterned film will not increase their roughness, either.

In addition, the post-baking step d) is also performed

10 in a vacuum, so the gas like CO_2 gas emanates again from the resist film at this post-baking step d). Accordingly, when the resist film is dry-developed (i.e., plasma-etched) using a silylated layer as a hard mask or when a patterned film is formed by etching an original film with a plasma, the gas re-

15 leased from the resist film will not mix with the plasma generated in the chamber. For that reason, the chemical composition of the plasma will not change during the plasma etching process.

Furthermore, the pre-baking, exposing, post-baking and

20 silylating steps b), c), d) and e) are performed in a vacuum without subjecting the resist film to the air. Thus, the resist film, made of a chemically amplified resist material, is not affected by an alkaline substance like ammonia contained in the air, and no insoluble layer, difficult to dissolve in

25 an alkaline developer, is formed on the surface of the resist

film. Consequently, a good silylated layer can be formed on the surface of the resist film and a fine-line resist pattern can be defined just as intended.

Particularly, according to the sixth method, the pre-
5 and post-baking steps b) and d) are performed in a chamber different from any of the chambers in which the exposing, si-lylating and dry-developing steps c), e) and f) are per-formed. In addition, a much smaller quantity of gas is released in the exposing step c). Accordingly, almost no re-
10 actants will deposit themselves on the surface of the resist film, photomask or optical system including mirrors. Conse-quently, the resist pattern will not be deformed or the EUV radiation exposure dose will not decrease.

As described above, according to the first through sixth
15 inventive pattern forming methods, a gas like CO_2 gas is given off from the resist film in the pre-baking step b). Thus, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step c). That is to say, in
20 this exposing step c), the reactants, usually produced by the gas emanated from the resist film during the exposure, will not deposit themselves on the walls of the resultant resist pattern. As a result, the resist pattern can have the very cross-sectional shape originally designed.

25 In one embodiment of the present invention, the pre-

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baking step b) preferably includes heating the resist film while irradiating the resist film with a type of radiation having too long a wavelength to sensitize the resist film.

Then, an even greater quantity of gas is released from the resist film in the pre-baking step b), thus increasing the throughput of the gas released and further suppressing the degassing phenomenon in the exposing step.

A first inventive apparatus for fabricating a semiconductor device includes first, second and third processing chambers. In the first processing chamber, a resist film is formed out of a resist material on a substrate and a resist pattern is defined on the substrate by developing the resist film that has been exposed to extreme ultraviolet radiation. The second processing chamber is filled with a vacuum, and is used to pre-bake the resist film. The third processing chamber is also filled with a vacuum and is used to expose the pre-baked resist film to the extreme ultraviolet radiation through a photomask.

In the first apparatus, the pre-baking step can be carried out in the second processing chamber filled with a vacuum, so a gas like CO_2 gas is given off from the resist film in this pre-baking step. Accordingly, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing step, the

reactants, usually produced by the CO_2 gas, etc., emanated from the resist film during the exposure, will not deposit themselves on the walls of the resultant resist pattern. This is because the gas has already been released in the pre-
5   vious pre-baking step.   Thus, those walls of the resist pattern much less likely increase their roughness.   As a result, the walls of the patterned film will not increase their roughness, either.

In addition, the pre-baking and exposing steps are per-
10 formed in mutually different processing chambers.   Moreover, a much smaller quantity of gas is released in the exposing step.   Accordingly, almost no reactants will deposit themselves on the surface of the resist film, photomask or optical system including mirrors.   Consequently, the resist
15 pattern will not be deformed or the EUV radiation exposure dose will not decrease.

A second inventive apparatus for fabricating a semiconductor device also includes first, second and third processing chambers.   In the first processing chamber, a resist film
20 is formed out of a chemically amplified resist material on a substrate and a resist pattern is defined on the substrate by developing the resist film that has been exposed to extreme ultraviolet radiation.   The second processing chamber is filled with a vacuum and is used to pre- and post-bake the
25 resist film before and after the resist film is exposed to the

extreme ultraviolet radiation, respectively. The third proc-
essing chamber is also filled with a vacuum and is used to
expose the pre-baked resist film to the extreme ultraviolet
radiation through a photomask.

5   In the second apparatus, the pre-baking step can be car-
ried out in the second processing chamber filled with a vac-
uum, so a gas like CO_2 gas is given off from the resist film
in this pre-baking step. Accordingly, even if the resist
film is exposed to high-energy EUV radiation in a vacuum af-
10 ter that, the degassing phenomenon rarely occurs in that ex-
posing step. That is to say, in this exposing step, the
reactants, usually produced by the CO_2 gas, etc., emanated
from the resist film during the exposure, will not deposit
themselves on the walls of the resultant resist pattern.
15 This is because the gas has already been released in the pre-
vious pre-baking step. Thus, those walls of the resist pat-
tern much less likely increase their roughness. As a result,
the walls of the patterned film will not increase their
roughness, either.

20   In addition, the pre- and post-baking steps are per-
formed in a chamber different from a chamber in which the ex-
posing step is performed. Moreover, a much smaller quantity
of gas is released in the exposing step. Accordingly, almost
no reactants will deposit themselves on the surface of the
25 resist film, photomask or optical system including mirrors.

Consequently, the resist pattern will not be deformed or the EUV radiation exposure dose will not decrease.

Furthermore, the pre-baking, exposing and post-baking steps are performed in a vacuum without subjecting the resist
5 film to the air. Thus, the resist film, made of a chemically amplified resist material, is not affected by an alkaline substance like ammonia contained in the air, and no insoluble layer, difficult to dissolve in an alkaline developer, is formed on the surface of the resist film. Consequently, a
10 fine-line resist pattern can be formed just as intended.

A third inventive apparatus for fabricating a semiconductor device includes first, second, third, fourth and fifth processing chambers. In the first processing chamber, a resist film is formed out of a chemically amplified resist ma-
15 terial on a substrate. The second processing chamber is filled with a vacuum and is used to pre- and post-bake the resist film before and after the resist film is exposed to extreme ultraviolet radiation, respectively. The third processing chamber is also filled with a vacuum and is used to
20 expose the pre-baked resist film to the extreme ultraviolet radiation through a photomask. In the fourth processing chamber, a silylated layer is formed selectively on the surface of the post-baked resist film. And in the fifth processing chamber, a resist pattern is defined on the substrate by dry-
25 developing the resist film, on which the silylated layer has

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been formed, using the silylated layer as a hard mask.

In the third apparatus, the pre-baking step can be carried out in the second processing chamber filled with a vacuum, so a gas like CO_2 gas is given off from the resist film

5 in this pre-baking step. Accordingly, even if the resist film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing step, the reactants, usually produced by the CO_2 gas, etc., emanated

10 from the resist film during the exposure, will not deposit themselves on the walls of the resultant resist pattern. This is because the gas has already been released in the previous pre-baking step. Thus, those walls of the resist pattern much less likely increase their roughness. As a result,

15 the walls of the patterned film will not increase their roughness, either.

In addition, the pre- and post-baking steps are performed in a chamber different from a chamber in which the exposing step is performed. Moreover, a much smaller quantity

20 of gas is released in the exposing step. Accordingly, almost no reactants will deposit themselves on the surface of the resist film, photomask or optical system including mirrors. Consequently, the resist pattern will not be deformed or the EUV radiation exposure dose will not decrease.

25 Furthermore, the pre-baking, exposing, post-baking and

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silylating steps are performed in a vacuum without subjecting the resist film to the air. Thus, the resist film, made of a chemically amplified resist material, is not affected by an alkaline substance like ammonia contained in the air, and no

5 insoluble layer, difficult to dissolve in an alkaline developer, is formed on the surface of the resist film. In addition, the acid can diffuse sufficiently in the pre-baking step, so the contact between exposed and non-exposed portions improves. Accordingly, a good silylated layer can be formed

10 on the surface of the resist film. Consequently, a fine-line resist pattern can be formed accurately enough.

As described above, the first through third inventive apparatuses can release a gas like CO_2 gas from the resist film in the pre-baking step. Accordingly, even if the resist

15 film is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing step, the reactants, usually produced by the gas emanated from the resist film during the exposure, will not deposit themselves on

20 the walls of the resultant resist pattern. As a result, the resist pattern can have the very cross-sectional shape originally designed.

In one embodiment of the present invention, the second processing chamber preferably includes means for irradiating

25 the resist film with a type of radiation having too long a

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wavelength to sensitize the resist film.

Then, an even greater quantity of gas is released from the resist film in the pre-baking step, thus further suppressing the degassing phenomenon in the exposing step.

5   In another embodiment of the present invention, the second processing chamber preferably includes means for exhausting a gas, emanated from the resist film, out of the second processing chamber.

Then, it is possible to avoid an unwanted situation 10 where the gas, released from the resist film in the pre-baking step, re-produce those harmful reactants that easily deposit themselves on the surface of the resist film.

BRIEF DESCRIPTION OF THE DRAWINGS

15   FIGS. **1A** through **1D** are cross-sectional views illustrating respective process steps for forming a resist pattern according to a first embodiment of the present invention.

FIGS. **2A** through **2E** are cross-sectional views illustrating respective process steps for forming a resist pattern ac-20 cording to a second embodiment of the present invention.

FIGS. **3A** through **3F** are cross-sectional views illustrating respective process steps for forming a resist pattern according to a third embodiment of the present invention.

FIG. **4** is a block diagram illustrating an apparatus for 25 fabricating a semiconductor device by carrying out a pattern

forming method according to a fourth embodiment of the present invention.

FIG. **5** is a block diagram illustrating an apparatus for fabricating a semiconductor device by carrying out a pattern forming method according to a fifth embodiment of the present invention.

FIG. **6** is a block diagram illustrating an apparatus for fabricating a semiconductor device by carrying out a pattern forming method according to a sixth embodiment of the present invention.

FIG. **7** is a cross-sectional view schematically illustrating the second processing chamber of an apparatus for fabricating a semiconductor device by carrying out the pattern forming method of the fourth, fifth or sixth embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

EMBODIMENT 1

Hereinafter, a resist pattern forming method according to a first embodiment of the present invention will be described with reference to FIGS. **1A** through **1D**.

First, as shown in FIG. **1A**, the surface of a semiconductor substrate **10** is coated with a normal (i.e., non-chemically-amplified) photoresist material using a spin coater, thereby forming a resist film **11** with a thickness of 130 nm, for example.

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Next, as shown in FIG. **1B**, the resist film **11** is pre-baked in a vacuum of about 1.0×10^{-5} Pa by getting the substrate **10** heated by a heater **12** to about 90℃ for about 60 seconds, for example. As a result of this pre-baking process step, a solvent vaporizes from the resist film **11** and a gas (e.g., CO_2 gas) is released from the resist film **11**. If the pre-baked resist film **11** is left in the vacuum for about 300 seconds, then the resist film **11** further gives off the gas like the CO_2 gas.

Then, as shown in FIG. **1C**, the resist film **11** is exposed to EUV radiation in a vacuum of about 1.0×10^{-6} Pa. Specifically, the EUV radiation is emitted from an EUV radiation source (not shown) at a wavelength of around 13 nm, for example, directed toward a reflective mask **13** and then reflected therefrom. Subsequently, the reflected part **14** of the EUV radiation is condensed by a reflection/demagnification optical system **15** to about 1/5, for example, and then allowed to be incident onto the resist film **11**. As a result, the resist film **11** comes to have exposed and non-exposed portions **11a** and **11b**.

In the illustrated embodiment, radiation with a wavelength of around 13 nm is used as the EUV radiation. Alternatively, any other radiation with a wavelength somewhere between 3 and 50 nm may also be used. The reflective mask **13** may be of any type. For example, the reflective mask **13** may

include a mask pattern formed on an EUV radiation reflective film. The mask pattern may be made of tantalum, which absorbs EUV radiation, while the EUV radiation reflective film may be a stack of molybdenum and silicon films. The reflec-

5   tion/demagnification optical system **15** may be made up of several reflective mirrors, each having a stack of molybdenum and silicon films as its reflective surface.

In the first embodiment, as shown in FIG. **1D**, the resist film **11** is subjected to a wet developing process in the air using a de-

10 veloper of xylene, for example, thereby forming a resist pattern **16** on the substrate **10** out of the non-exposed portions **11b** of the resist film **11**.

In the first embodiment, the pre-baking step is carried out in a vacuum, so a gas like CO_2 gas is given off from the

15 resist film **11** in this pre-baking step. Accordingly, even if the resist film **11** is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing step, the reactants, usually produced by the CO_2 gas, etc.,

20 emanated from the resist film **11** during the exposure, will not deposit themselves on the walls of the resultant resist pattern **16**. This is because the gas has already been released in the previous step. Thus, those walls of the resist pattern **16** much less likely increase their roughness. Ac-

25 cordingly, when a film to be etched, which has been deposited

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on the substrate **10**, is dry-etched and patterned, the walls of the patterned film will not increase their roughness, either.

5 EMBODIMENT 2

Hereinafter, a resist pattern forming method according to a second embodiment of the present invention will be described with reference to FIGS. **2A** through **2E**.

First, as shown in FIG. **2A**, the surface of a semiconduc-
10 tor substrate **20** is coated with a chemically amplified photoresist material using a spin coater, thereby forming a resist film **21** with a thickness of 130 nm, for example. The chemically amplified photoresist material may be a polyvinyl phenol resin including a protecting group of tertiary butoxy
15 carbonyl (t-BOC).

Next, as shown in FIG. **2B**, the resist film **21** is pre-baked in a vacuum of about 1.0×10^{-5} Pa by getting the substrate **20** heated by a heater **22** to about 110 ℃ for about 60 seconds, for example. As a result of this pre-baking process
20 step, a solvent vaporizes from the resist film **21** and a gas (e.g., CO_2 gas) is given off from the resist film **21**. If the pre-baked resist film **21** is left in the vacuum for about 300 seconds, then the resist film **21** further gives off the gas like the CO_2 gas.

25 Then, as shown in FIG. **2C**, the resist film **21** is exposed

to EUV radiation in a vacuum of about 1.0×10^{-6} Pa. Specifically, the EUV radiation is emitted from an EUV radiation source (not shown) at a wavelength of around 13 nm, for example, directed toward a reflective mask **23** and then reflected therefrom. Subsequently, the reflected part **24** of the EUV radiation is condensed by a reflection/demagnification optical system **25** to about 1/5, for example, and then allowed to be incident onto the resist film **21**. As a result, the resist film **21** comes to have exposed and non-exposed portions **21a** and **21b**. In the illustrated embodiment, radiation with a wavelength of around 13 nm is used as the EUV radiation. Alternatively, any other radiation with a wavelength somewhere between 3 and 50 nm may also be used. The reflective mask **13** and reflection/demagnification optical system **25** may be the same as those used for the first embodiment.

Thereafter, as shown in FIG. **2D**, the resist film **21** is post-baked in a vacuum of about 1.0×10^{-5} Pa by getting the substrate **20** heated again by a heater **26** to 130℃ for 60 seconds, for example. Then, the acid, which has been generated in the exposed or non-exposed portions **21a** or **21b** of the resist film **21** as a result of the exposure process, further diffuses and the gas like the CO_2 gas further emanates from the resist film **21**.

Finally, as shown in FIG. **2E**, the resist film **21** is subjected to a wet developing process in the air using a devel-

oper of trimethylammonium hydroxide (TMAH), for example, thereby forming a resist pattern **27** on the substrate **20** out of the non-exposed portions **21b** of the resist film **21**.

5   In the second embodiment, the pre-baking step is carried out in a vacuum, so a gas like CO_2 gas is given off from the resist film **21** in this pre-baking step. Accordingly, even if the resist film **21** is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing 10 step, the reactants, usually produced by the CO_2 gas, etc., emanated from the resist film **21** during the exposure, will not deposit themselves on the walls of the resultant resist pattern **27**. This is because the gas has already been released in the previous step. Thus, those walls of the resist 15 pattern **27** much less likely increase their roughness. Accordingly, when a film to be etched, which has been deposited on the substrate **20**, is dry-etched and patterned, the walls of the patterned film will not increase their roughness, either.

20   In addition, the post-baking step is also performed in a vacuum. Accordingly, where a patterned film is formed by etching an original film with a plasma, the gas released from the resist film **21** will not mix with the plasma generated in the chamber. For that reason, the chemical composition of 25 the plasma will not change during the plasma etching process,

so the walls of the patterned film will not increase their roughness.

EMBODIMENT 3

5   Hereinafter, a resist pattern forming method according to a third embodiment of the present invention will be described with reference to FIGS. **3A** through **3F**.

First, as shown in FIG. **3A**, the surface of a semiconductor substrate **30** is coated with a chemically amplified pho-

10   toresist material using a spin coater, thereby forming a resist film **31** with a thickness of 130 nm, for example.

Next, as shown in FIG. **3B**, the resist film **31** is pre-baked in a vacuum of about 1.0×10^{-5} Pa by getting the substrate **30** heated by a heater **32** to about 110 ℃ for about 60

15   seconds, for example. As a result of this pre-baking process step, a solvent vaporizes from the resist film **31** and a gas (e.g., CO_2 gas) is given off from the resist film **31**. If the pre-baked resist film **31** is left in the vacuum for about 300 seconds, then the resist film **31** further gives off the gas

20   like the CO_2 gas.

Then, as shown in FIG. **3C**, the resist film **31** is exposed to EUV radiation in a vacuum of about 1.0×10^{-6} Pa. Specifically, the EUV radiation is emitted from an EUV radiation source (not shown) at a wavelength of around 13 nm, for exam-

25   ple, directed toward a reflective mask **33** and then reflected

therefrom. Subsequently, the reflected part **34** of the EUV radiation is condensed by a reflection/demagnification optical system **35** to about 1/5, for example, and then allowed to be incident onto the resist film **31**. As a result, the resist film **31** comes to have exposed and non-exposed portions **31a** and **31b**. In the illustrated embodiment, radiation with a wavelength of around 13 nm is used as the EUV radiation. Alternatively, any other radiation with a wavelength somewhere between 3 and 50 nm may also be used. The reflective mask **33** and reflection/demagnification optical system **35** may be the same as those used for the first embodiment.

Thereafter, as shown in FIG. **3D**, the resist film **31** is post-baked in a vacuum of about 1.0×10^{-5} Pa by getting the substrate **30** heated again by a heater **36** to 130℃ for 60 seconds, for example. Then, the acid, which has been generated in the exposed or non-exposed portions **31a** or **31b** of the resist film **31** as a result of the exposure process, further diffuses and the gas like the CO_2 gas further emanates from the resist film **31**.

Next, a silylating agent is supplied onto the surface of the resist film **31**, thereby forming a silylated layer **37** selectively on the exposed or non-exposed portions **31a** or **31b**, in which the acid has been generated as a result of the exposure process, as shown in FIG. **3E**. In the example illustrated in FIG. **3E**, the acid has been generated in the non-exposed

portions **31b**.

Finally, the resist film **31** is dry-developed (i.e., plasma-etched) using the silylated layer **37** as a hard mask, thereby forming a resist pattern **38** on the substrate **30** out of
5   the non-exposed portions **31b** of the resist film **31**.

In the third embodiment, the pre-baking step is carried out in a vacuum, so a gas like CO_2 gas is given off from the resist film **31** in this pre-baking step. Accordingly, even if the resist film **31** is exposed to high-energy EUV radiation in
10 a vacuum after that, the degassing phenomenon rarely occurs in that exposing step. That is to say, in this exposing step, the reactants, usually produced by the CO_2 gas, etc., emanated from the resist film **31** during the exposure, will not deposit themselves on the walls of the resultant resist
15 pattern **38**. This is because the gas has already been re-leased in the previous step. Thus, those walls of the resist pattern **38** much less likely increase their roughness. Ac-cordingly, when a film to be etched, which has been deposited on the substrate **30**, is dry-etched and patterned, the walls
20 of the patterned film will not increase their roughness, ei-ther.

In addition, the post-baking step is also performed in a vacuum. Accordingly, when the resist film **31** is dry-developed (i.e., plasma-etched) to define the resist pattern
25 **38** or when a patterned film is formed by etching an original

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film with a plasma, the gas released from the resist film **31** will not mix with the plasma generated in the chamber. For that reason, the chemical composition of the plasma will not change during the plasma etching process. As a result, a

5 good resist pattern can be defined and the walls of the patterned film will not increase their roughness.

EMBODIMENT 4

Hereinafter, a resist pattern forming method according

10 to a fourth embodiment of the present invention and an apparatus for fabricating a semiconductor device for use in the method of the fourth embodiment will be described with reference to FIGS. **1A** through **1D** and **4**.

First, as shown in FIG. **1A,** the surface of a semiconduc-

15 tor substrate **10** is coated with a normal (i.e., non-chemically-amplified) photoresist material in a first processing chamber **110** filled with the air at the atmospheric pressure, thereby forming a resist film **11** thereon.

Next, the substrate **10** is transported in line from the

20 first processing chamber **110** to a second processing chamber **120** filled with a vacuum of about 1.0×10^{-5} Pa. Then, in the second processing chamber **120,** the resist film **11** is pre-baked by getting the substrate **10** heated by a heater **12** to about 90℃ for about 60 seconds, for example, as shown in FIG. **1B.**

25 In this manner, a solvent is vaporized from the resist film **11**

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and a gas (e.g., CO_2 gas) is given off from the resist film **11**.

Subsequently, the substrate **10** is transported in line from the second processing chamber **120** to a third processing chamber **130** filled with a vacuum of about 1.0×10^{-6} Pa. Then,

5   in the third processing chamber **130**, the resist film **11** is exposed to EUV radiation as shown in FIG. **1C**. Specifically, the EUV radiation with a wavelength of around 13 nm, for example, is directed toward a reflective mask **13** and then reflected therefrom. Subsequently, the reflected part **14** of the EUV ra-

10   diation is condensed by a reflection/demagnification optical system **15** to about 1/5, for example, and then allowed to be incident onto the resist film **11**. As a result, the resist film **11** comes to have exposed and non-exposed portions **11a** and **11b**.

15   Thereafter, the substrate **10** is transported in line from the third processing chamber **130** to the first processing chamber **110**. Then, in the first processing chamber **110**, the resist film **11** is subjected to a wet developing process, thereby forming a resist pattern **16** on the substrate **10** out of the

20   non-exposed portions **11b** of the resist film **11** as shown in FIG. **1D**.

In the fourth embodiment, the pre-baking step is carried out in a vacuum, so a gas like CO_2 gas is given off from the resist film **11** in this pre-baking step. Accordingly, even if

25   the resist film **11** is exposed to high-energy EUV radiation in

a vacuum after that, the degassing phenomenon rarely occurs in that exposing step.

It is not impossible to perform both the pre-baking and EUV exposure process steps in the same vacuum chamber. In that case, however, the reactants, produced by the CO_2 gas, etc., emanated from the resist film **11** in the pre-baking process step, might deposit themselves on the surface of the resist film **11**, reflective mask **13** or optical system including the mirrors. If those reactants deposit themselves on the surface of the resist film **11**, then the resist pattern **16** might be deformed. And if the reactants deposit themselves on the surface of the reflective mask **13** or mirrors, then the exposure dose of the resist film **11**, or the amount of EUV radiation reflected off from the mask **13** or mirrors and then reaching the resist film **11**, might decrease.

In contrast, according to the fourth embodiment, the pre-baking and exposing steps are performed in mutually different processing chambers. Accordingly, almost no reactants will deposit themselves on the surface of the resist film **11**, reflective mask **13** or optical system including mirrors. Consequently, the resist pattern **16** will not be deformed or the EUV radiation exposure dose will not decrease.

EMBODIMENT 5

Hereinafter, a resist pattern forming method according

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to a fifth embodiment of the present invention and an appara-
tus for fabricating a semiconductor device for use in the
method of the fifth embodiment will be described with refer-
ence to FIGS. **2A** through **2E** and **5**.

5   First, the surface of a semiconductor substrate **20** is
coated with a chemically amplified photoresist material in a
first processing chamber **210** filled with the air at the atmos-
pheric pressure, thereby forming a resist film **21** thereon as
shown in FIG. **2A**.

10   Next, the substrate **20** is transported in line from the
first processing chamber **210** to a second processing chamber
220 filled with a vacuum of about 1.0×10^{-5} Pa. Then, in the
second processing chamber **220**, the resist film **21** is pre-baked
by getting the substrate **20** heated by a heater **22** to about
15   110°C for about 60 seconds, for example, as shown in FIG. **2B**.
In this manner, a solvent is vaporized from the resist film **21**
and a gas (e.g., CO_2 gas) is given off from the resist film **21**.

       Thereafter, the substrate **20** is transported in line from
the second processing chamber **220** to a third processing cham-
20   ber **230** filled with a vacuum of about 1.0×10^{-6} Pa. Then, in
the third processing chamber **230**, the resist film **21** is ex-
posed to EUV radiation as shown in FIG. **2C**. Specifically, the
EUV radiation with a wavelength of around 13 nm, for example,
is directed toward a reflective mask **23** and then reflected
25   therefrom. Subsequently, the reflected part **24** of the EUV ra-

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diation is condensed by a reflection/demagnification optical system **25** to about 1/5, for example, and then allowed to be incident onto the resist film **21**. As a result, the resist film **21** comes to have exposed and non-exposed portions **21a** and **21b**.

Thereafter, the substrate **20** is transported in line from the third processing chamber **230** to the second processing chamber **220**. Then, in the second processing chamber **220**, the resist film **21** is post-baked by getting the substrate **20** heated again by a heater **26** to 130℃ for 60 seconds, for example, as shown in FIG. **2D**. In this manner, the acid, which has been generated in the exposed or non-exposed portions **21a** or **21b** of the resist film **21** as a result of the exposure process, further diffuses and the gas like the CO_2 gas further emanates from the resist film **21**.

Subsequently, the substrate **20** is transported in line from the second processing chamber **220** to the first processing chamber **210**. Then, in the first processing chamber **210**, the resist film **21** is subjected to a wet developing process using a developer of TMAH, for example, thereby forming a resist pattern **27** on the substrate **20** out of the non-exposed portions **21b** of the resist film **21** as shown in FIG. **2E**.

In the fifth embodiment, the pre- and post-baking steps are carried out in a vacuum, so a gas like CO_2 gas is given off from the resist film **21** in these pre- and post-baking

steps. Accordingly, even if the resist film **21** is exposed to high-energy EUV radiation in a vacuum after that, the de-gassing phenomenon rarely occurs in that exposing step. Moreover, the chemical composition of the plasma will not

5 change while the film to be patterned is plasma-etched.

Also, the pre- and post-baking steps are performed in a chamber different from the chamber in which the exposing step is performed. In addition, a much smaller quantity of gas is released in the exposing step. Accordingly, almost no reac-

10 tants will deposit themselves on the surface of the resist film **21**, reflective mask **23** or optical system including mir-rors. Consequently, the resist pattern **27** will not be de-formed or the EUV radiation exposure dose will not decrease.

15 EMBODIMENT 6

Hereinafter, a resist pattern forming method according to a sixth embodiment of the present invention and an appara-tus for fabricating a semiconductor device for use in the method of the sixth embodiment will be described with refer-

20 ence to FIGS. **3A** through **3F** and **6**.

First, the surface of a semiconductor substrate **30** is coated with a chemically amplified photoresist material in a first processing chamber **310** filled with the air at the atmos-pheric pressure, thereby forming a resist film **31** thereon as

25 shown in FIG. **3A**.

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Next, the substrate **30** is transported in line from the first processing chamber **310** to a second processing chamber **320** filled with a vacuum of about 1.0×10^{-5} Pa. Then, in the second processing chamber **320**, the resist film **31** is pre-baked by getting the substrate **30** heated by a heater **32** to about 110℃ for about 60 seconds, for example, as shown in FIG. **3B**. In this manner, a solvent is vaporized from the resist film **31** and a gas (e.g., CO_2 gas) is given off from the resist film **31**.

Subsequently, the substrate **30** is transported in line from the second processing chamber **320** to a third processing chamber **330** filled with a vacuum of about 1.0×10^{-5} Pa. Then, in the third processing chamber **330**, the resist film **31** is exposed to EUV radiation as shown in FIG. **3C**. Specifically, the EUV radiation with a wavelength of around 13 nm, for example, is directed toward a reflective mask **33** and then reflected therefrom. Subsequently, the reflected part **34** of the EUV radiation is condensed by a reflection/demagnification optical system **35** to about 1/5, for example, and then allowed to be incident onto the resist film **31**. As a result, the resist film **31** comes to have exposed and non-exposed portions **31a** and **31b**.

Thereafter, the substrate **30** is transported in line from the third processing chamber **330** to the second processing chamber **320**. Then, in the second processing chamber **320**, the resist film **31** is post-baked by getting the substrate **30** heat-

ed again by a heater **36** to 130℃ for 60 seconds, for example, as shown in FIG. **3D.** In this manner, the acid, which has been generated in the exposed or non-exposed portions **31a** or **31b** of the resist film **31** as a result of the exposure process, fur-

5 ther diffuses and the gas like the CO_2 gas further emanates from the resist film **31.**

Next, the substrate **30** is transported in line from the second processing chamber **320** to a fourth processing chamber **340** filled with a vacuum of about 1.0×10^{-5} Pa. Then, in the

10 fourth processing chamber **340**, a silylating agent is supplied onto the surface of the resist film **31.** In this manner, a si-lylated layer **37** is formed on the exposed or non-exposed por-tions **31a** or **31b,** in which the acid has been generated as a result of the exposure process, as shown in FIG. **3E.**

15 Subsequently, the substrate **30** is transported in line from the fourth processing chamber **340** to a fifth processing chamber **350** filled with a vacuum of about 1.0×10^{-6} Pa. Then, in the fifth processing chamber **350**, the resist film **31** is dry-developed using the silylated layer **37** as a hard mask,

20 thereby forming a resist pattern **38** on the substrate **30** out of the non-exposed portions **31b** of the resist film **31** as shown in FIG. **3F.**

In the sixth embodiment, the pre-baking step is carried out in a vacuum, so a gas like CO_2 gas is given off from the

25 resist film **31** in this pre-baking step. Accordingly, even if

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the resist film **31** is exposed to high-energy EUV radiation in a vacuum after that, the degassing phenomenon rarely occurs in that exposing step.

In addition, the post-baking step is also performed in a vacuum. Accordingly, when the resist film **31** is dry-developed (i.e., plasma-etched) to define the resist pattern **38** or when a patterned film is formed by etching an original film with a plasma, the gas released from the resist film **31** will not mix with the plasma generated in the chamber. For that reason, the chemical composition of the plasma will not change during the plasma etching process. As a result, a good resist pattern can be defined and the walls of the patterned film will not increase their roughness.

FIG. 7 illustrates a cross-sectional structure for the second processing chamber **120**, **220** or **320** of the fourth, fifth or sixth embodiment. As shown in FIG. **7**, a lamp **401** for irradiating the resist film **11**, **21** or **31** with radiation (e.g., visible light) with too long a wavelength to sensitize the resist film **11**, **21** or **31** is disposed on the ceiling of the second processing chamber **120**, **220** or **320**. Accordingly, in the pre-baking process step, the resist film **11**, **21** or **31** can be heated while being irradiated with the long-wavelength radiation. As a result, the resist film **11**, **21** or **31** gives off an even greater quantity of gas.

As also shown in FIG. **7**, the second processing chamber

120, 220 or 320 further includes means for exhausting the gas produced in the chamber 120, 220 or 320, e.g., a turbo pump 402 with a very large stroke volume. Accordingly, the gas (e.g., CO_2 gas), given off from the resist film 11, 21 or 31

5   in the pre-baking process step, can be forced out of the chamber 120, 220 or 320. Thus, it is possible to avoid an unwanted situation where the gas, released from the resist film 11, 21 or 31, re-produce the harmful reactants that easily deposit themselves on the surface of the resist film 11, 21

10   or 31, reflective mask 13, 23 or 33 or mirrors.